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RELATIONSHIPS BETWEEN TECTONIC AND GEOMORPHOLOGICAL LINEAR FEATURES IN THE GUADIX-BAZA BASIN, SOUTHERN SPAIN

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ABSTRACT

Linear elements of the landscape of the Guadix-Baza basin, southern Spain, were identified from a Landsat TM image. Three important lineament trends have been identified in the Guadix-Baza basin. The first is NE–SW, which is the dominant trend in the basin; the second is NW–SE, and the third is ENE–WSW. These three trends are correlated to the major faults of the Guadix-Baza basin. The study of linear features by the analysis of satellite data has revealed a strong link between the buried tectonic structures and the morphological features appearing at the surface. The distribution and density of lineaments explains much of the morphology of the land surface. It is possible to reconstruct elements of the tectonic and denudational history of the region and show that during Quaternary times lineaments controlled the sedimentation of the basin and the drainage pattern. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: linear features; image processing; tectonics; geomorphology; Guadix-Baza basin

INTRODUCTION

Regional synoptic data from satellite images provide information on surface morphology from which associated tectonic activity may be inferred through identification of linear features. Such linear features are the expression of the relationships between the terrain morphology and geological faults at different scales (Saunders and Hicks, 1976). These are manifested in both hard and soft rocks and can be used to delineate specific features such as areas of seismic and landslide risk (Alexander and Renzo, 1993). In the Guadix-Baza basin of southern Spain, the rocks are predominantly soft, being of Plio-Pleistocene age. This paper deals with the identification of linear elements of a Landsat image of the Guadix-Baza basin, the inference about geological lineaments and the association between these lineaments and geomorphic features also identified from the image. It goes on to attempt an interpretation of tectonic structures and their relation to the landscape of the region.

Identifying linear features depends on two factors. First the association between faulting and surface expression that is manifest in images, and secondly, on the interpretation of the identified features as being of tectonic origin. The principal problem this paper addresses is about the association of tectonic features with geomorphic ones. This involves establishing relations between the two based on interpretation of image data alone. Linear features are identified from ground surface properties. Identifying tectonic linear features is based on assumptions about the dependency on the nature of the geological fault, the ground conditions and subsequent geomorphic processes which expose and emphasize the phenomenon. These are inferred from evidence based on image colour, texture, tone and pattern. A linear form is recognized where sufficiently continuous and coherent evidence of structure, which collectively the eye interprets as linear, are seen (Stefouli, 1983).

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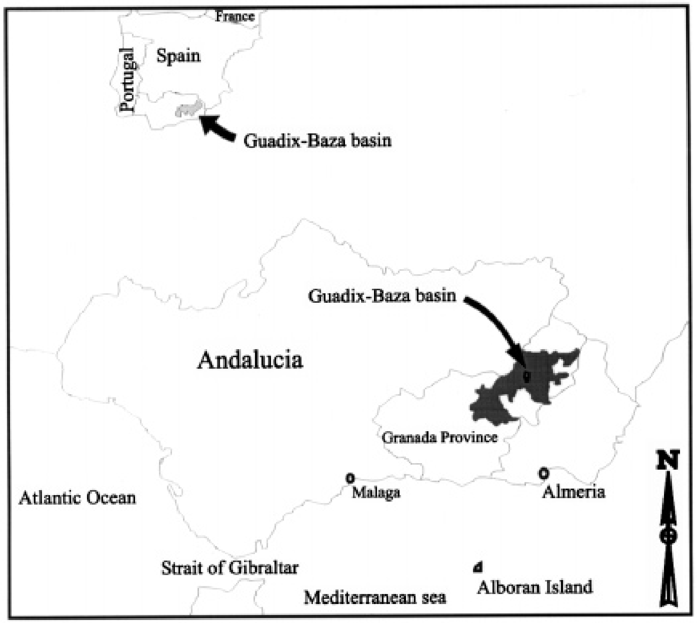

Figure 1. Location of the Guadix-Baza basin within the western Mediterranean

Evidence of geological linearity is taken when the collection of such elements is associated with a number of geomorphological features that can be independently recognized from image evidence. In this way it is possible to define extensive linear features whose interpretation does not depend on any single morphological feature. It is argued, therefore, that the interpretation of lineaments is independent of specific morphological features and that lineaments identified in this way are reasonably interpreted as geological. On this basis we can further examine the association of morphological feature types with linear forms that are interpreted as being of tectonic origin.

GEOLOGICAL BACKGROUND

The Guadix-Baza basin lies at the centre of the Betic Cordillera Alpine chain of southern Spain (Figure 1) and is located between the sedimentary formations of the External Zone to the north and the metamorphic rocks forming the Internal Zone to the south. During pre-Neogene time the Internal Zone was located hundreds of kilometres to the northeast of its present-day position (Sanz Degaldeano 1983, 1987, 1990). Owing to the lack of space in the western Mediterranean (Boccatelli *et al.*, 1986), it was pushed southwestwards by the collision of the African and European plates (Sanz Degaldeano, 1990). During Neogene times the Internal Zone collided along a strike-slip fault zone with the External Zone which formed part of the stable plate of the Spanish Meseta. The collision created several structural basins within the Betic Cordillera, the Guadix-Baza being one of them. The basins filled with sediments during Miocene, Pliocene and Quaternary times.

The sediments of the Guadix-Baza basin are, for the most part, of continental origin and are mainly of Pliocene and Quaternary age. The basin may be subdivided into a western and an eastern sector (Vera, 1970). The deposits in the western sector are represented by the fluviatile Guadix and the lagoonal Gorafe-Huelago Formations. In the eastern sector the sediments are represented by evaporitic deposits of the Baza Formation and the fluvial Sero-Caniles Formation. A pediplane developed on all these formations (Pena, R. 1978; 1985).

The fracture pattern of the Guadix-Baza basin is part of the overall fracture system of the Betic Cordillera. Three main families of fracture are present: the first, which runs in a N70°W direction, is clearly related to the tectonic movement of the Internal Zone towards the west. The other two systems, running N30° to 60°W and N10° to 30°E, respectively, are more recent and are associated with important lateral and vertical

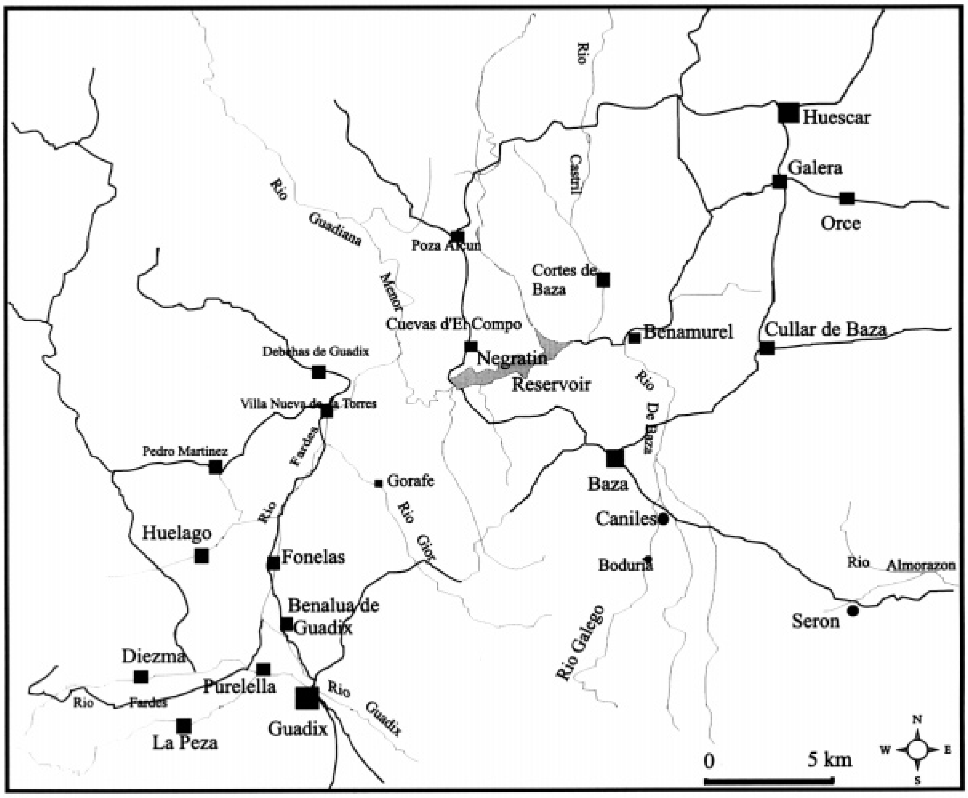

Figure 2. Drainage system and major localities of the Guadix-Baza basin

displacements, which have affected the topography of the area. The basement faults associated with the collision of the two zones are more apparent at the edges of the basin where some of them continue to be active and some have been reactivated during Quaternary times.

Research carried out in adjacent basins of the Betic Cordillera has shown that the direction of the main neotectonic stress shifted during the Quaternary from NE–SW to NNW–SSE (Ott d'Estevou and Montenat, 1985). Furthermore, the whole Betic Cordillera complex underwent general uplift during early Quaternary times, reaching a maximum during the middle of the Quaternary (Philip, H. and Bousquet, J., 1975).

IMAGE PROCESSING

The Landsat 5 TM scene used in the study was taken on 6 May 1989. It has six bands with a nominal resolution of 30 m. Image processing was conducted using EASI-PACE and System9 GIS, for vector analysis. The image was geometrically corrected and enhanced by various techniques, including contrast stretching, edge enhancement, band ratioing and principal components analysis (PCA). The area of the Guadix-Baza basin was extracted from the full scene and analysed at full resolution. Five sectors of the study area have been selected for more detailed study. These sectors are, Guadix and Gorafe in the western sector, Huescar and Baza with Banamurel in the eastern sector, and Negratin area in the centre of the basin (Figure 2). The images of these three areas were extracted and underwent the same processing operations. Linear features were identified from processed images and plotted using heads-up, on-screen digitizing. A sequence for identification was followed beginning with contrast-stretched images of new data. Further identification and assessment of plotted lineaments was undertaken with ratioed data when any ambiguous lineaments were

Table I. Summary of different ratios used in the study

Ratios	Drainage	Lineaments	Topography
B7/B5	Average	Very good	Poor
B7/B4	Poor	Average	Good
B7/B3	Good	Very good	Poor
B5/B4	Poor	Good	Good
B5/B3	Good	Good	Good
B7/B1	Good	Good	Poor
B5/B1	Good	Poor	Poor
B4/B1	Good	Poor	Good
B3/B1	Good	Poor	Good
(B7/B5)/(B7/B4)	Good	Very good	Poor
(B7 − B5)/(B7 + B5)	Good	Good	Poor

Table II. Different filters used in this study

F1	1	2	2	F2	1	1	1	F3	1	0	−1
	0	6	0		1	−9	1		2	0	−2
	1	−2	−1		−1	−1	−1		1	0	−1
F4	2	1	0	F5	−1	−2	−1	F6	−1	−1	−1
	1	0	−1		−2	13	−2		−1	8	−1
	0	−1	−2		−1	−2	−1		−1	−1	−1

F7	0	0	0	F8	−1	0	1
	−1	0	1		−1	0	1
	0	0	1		−1	0	1

deleted. The identification and editing sequence continued using filtered ratios and raw data, and PCA. Only lineaments which were identified at each stage and which could be interpreted as geological lineaments were included. Subsequent field checking was used on sample areas to confirm the existence of lineaments. Lineament maps from the images were produced and stored as overlays and later combined to produce a final map.

Ratios

Different combinations of TM bands were explored for geological interpretation. Bands 1, 3, 4, 5 and 7 were found to be the most useful for lineament detection. Band ratios were obtained using combinations of different bands. The following ratios were found to be the most useful for this study: B7/B5, B7/B4, B7/B3, B5/B4, B5/B3, B7/B1, B5/B1, B4/B1, B3/B1 (B7/B5)/(B7/B4) and (B7−B5)/(B7 + B5). The ratios B4/B3 and B5/B3 highlighted the location of streams, reservoirs, lakes and flooded areas. The structure relating to streams was recognizable because of the suppression of the topographic effect. Ratios such as B5/B3 and B5/B1 revealed more topographic structure together with the drainage pattern. However, geological features were suppressed and the dominant streams were particularly well revealed. Lineaments became prominent when using ratios B7/B5, B7/B3 and B7/B4, and were further enhanced by combining these ratios into a false colour composite. The results are summarized in Table I.

Spatial filtering

Images were enhanced using a small edge filter (3×3) after an initial stretching using square root or Gaussian algorithms. Other filters of 11×11, 7×7 and 5×5 were used as well, but proved to be less effective than the 3×3 pixel filter in delineating edges. Table II gives a summary of the filters used in this

Table III. Results of the spatial filtering on the morphology of the area

Filters	Drainage	Lineaments	Topography
F1	Poor	Good	Poor
F2	Good	Very good	Poor
F3	Poor	Average	Poor
F4	Good	Good	Poor
F5	Good	Very good	Good
F6	Good	Very good	Good
F7	Good	Good	Average
F8	Average	Average	Poor

Table IV. Model proposed for the classification of linear features (modified from Stefouli, 1983)

Classes	Geomorphological features
1. Relief features	Abrupt relief change features
	Positive relief features
2. Tonal features	Sharp tonal boundary features
	Tonal boundary features;
	a. Light tonal line features
	b. Dark tonal line features
3. Textural features	Textural line features
4. Drainage features	Straight stream line features
	Major stream course changes

study, and Table III shows the main effects of the filters on the images. The extraction of linear features was done by first displaying an edge-filtered image as one band with two other bands (bands 5 and 7). This display gave an overlay effect and facilitated the detection and delineation of linear features. Linear features were drawn on overlays, stored as bitplanes and exported for statistical analysis.

Principal components analysis

Principal components analysis (PCA) is a linear transformation technique used to minimize data redundancy and to enhance an area of subtle spectral difference. It compresses the multichannel image data by calculating a new coordinate system, so as to condense the scene variance in the original data into a new set of variables which are called principal components. Using these data a new image can be developed. Earlier work in the neighbouring areas has established that the main lithologies can be distinguished and mapped from Landsat TM images (Bussell, *et al.*, 1995). In the study, in the absence of a geological map, an attempt was made using PCA to map all lithological units. Lithologies identified in this way were used in the interpretation of the tectonics of the area. They were validated by field checking.

LINEAMENT ANALYSIS

The process of detection and classification of linear features is the main task of image analysis. This process is strongly linked with knowledge of the geomorphological characteristics, which define linear features. A model of linear feature classification based on work by Stefouli (1983) is proposed, modified to suit the geomorphic conditions and geological characteristics of the study area, and is recommended for use as a general model for the young Neogene basins of the Mediterranean region. Four main geomorphological classes have been defined to represent linear features as they appear on the different processed images (Table IV). These classes are: relief features, tonal features, textures features and drainage features.

(1) *Relief features* may differ from one area to another and may also appear differently for different type of images. However, the study area offers, more or less the same type of features throughout the basin. Abrupt relief features and positive relief features are the main elements of this class. They are represented

by (a) abrupt linear change of the average relief, which may be formed by trenches, valleys and cliffs; (b) low-relief linear scarps, alignment of springs, linear slope breaks in alluvial fans and abrupt changes in stream gradients; (c) abrupt topographic changes represented by the edges of scarps and valley edges.

Each of these elements can be distinguished on the images. The first elements appear on the images as a rapid change of tone and by the shadow they cause on the image. In general, positive relief features represent ridges. It is important to note that for this particular feature, knowledge of the geology and morphology of the area is crucial in defining them. These features were recognized by the effect of the shadowing which gives the impression of the elevation of the feature in respect of the surrounding topography. They appear as light tonal areas alongside a dark tonal area, which represents the shadow caused by the relief. Several such features are present in the study area, represented most of the time by high elevated terrain both inside the basin and at its edges.

(2) *Tonal features* are also identified on the basis of tonal contrast. Tonal changes that are described in this class are, however, different from the ones described in the first class. The tonal changes described in the first class are always associated with relief change as perceived by the human eye and the tonal change is abrupt, whereas for tonal features there is no association with relief or at most a very smooth relief expression is indicated.

(3) *Textural features* are used to differentiate between features of the same reflectance. Texture is associated with the overall change of erosional patterns, which is developed between different lithologies and along the line of weakness on the surface. Textural feature lines or texture boundaries are recognized as such when a change of textures occurs along a line. Textural boundaries may define the limits between different types of deposit as well as the nature of the contact between them.

(4) *Drainage features* are important parameters in defining some lineaments in the Guadix-Baza basin where the spatial arrangement of streams is closely related to the structures of the terrain. In the Guadix-Baza basin the drainage system is of relatively young age, i.e. most of the steams were formed during the Pliocene–Pleistocene period and up to the Pleistocene Wurm period (Viceras, 1991). This is supported by the fact that nearly all the Pliocene–Pleistocene formations and the pediplane level are cut into by stream channels. In this study, drainage features are considered as a geomorphological class because of their importance in the basin and their influence on the material filling the basin. Their young formation also may be a good indicator of the tectonic stress prevailing in and around the Guadix-Baza basin during its formation.

Orientation of lineament systems

The lineaments form a complex pattern throughout the study area. Differences in orientation and density are visible in the rose diagram shown in Figure 3, from which three major and four minor trends can be recognized.

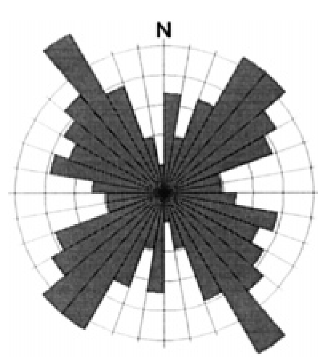

Figure 3. Rose diagram showing the main orientation of the linear features of the basin

Table V. The estimation of geological features by each geomorphological class (the calculation is approximate and is made on 1050 linear features)

	Relief features		Tonal features			Textural features	Drainage features	
	Abrupt relief features	Positive relief features	Sharp tonal features	Tonal lines: Dark	Tonal lines: Light		Straight stream lines	Major stream course changes
Faults	45% (50%)	5%	10%	3·5% (13·5%)	0·5%	25%	5% (10%)	5%
Fractures and joints	2% (2%)	–	1% (91%)	80%	5%	–	5%	– (5%)
Lithological contact	20% (22%)	2%	3% (8%)	5%	–	60%	2·5%	– (2·5%)
Bedding	– (1%)	1%	5%	30% (70%)	35%	–	1% (1%)	–
Folds	–	30% (30%)	10% (40%)	30%	–	–	20% (20%)	–

Major trends:

(i) *The NE–SW trend*. This is the dominant trend in the study area. The lineaments falling in this trend are the longest in the basin. This trend is parallel to: (a) some of the major regional faults shown on Sanz Degaldeano's (1983) tectonic map of the Betic Cordillera; (b) a major fault running east of the Benalua de Guadix.

(ii) *The NW–SE trend*. This is the second most important trend and it is most common in the central part of the study area. It is parallel (a) to the Negratin fault, (b) to some basement faults of the Internal/External Zones, and (c) to the contact of the Internal/External Zones.

(iii) *The ENE–WSW trend*. This is the third most important trend. It is present throughout the study area.

Minor trends:

(iv) *The NNW–SSE trend*. This is less common than those trends referred above. It is parallel to some mapped faults. At most locations it affects recent materials of the pediplane and it coincides with a mapped fault affecting the Quaternary deposits. It coincide as well, in the Baza area, with a known fault (Baza fault) which is suspected to be a regional fault (Sanz Degaldeano, 1987).

(v) *The NNE–SSW trend*. This is not a dominant set and is found only in some southern parts of the basin. This trend defines some fracturing in the Baza and Huescar area. The NNE–SSW and the NNW–SSE seems to exert a major control over the morphology of the badlands areas where the cuestas forming the bulk of the badlands generally take this orientation. These two trends, however, are not common in the basin as a whole and when they occur, they cross only the recent material of Pleistocene age.

(vi) *The WNW–ESE trend*. This trend is less common and it is present mainly in the recent material of Plio-Pleistocene age.

(vii) *The E–W and N–S trends*. These two trends are present but not in all areas. These two trends are associated with the most recent faulting in the Negratin and Huescar area.

Geomorphological relation to linear features

The major and minor trends of the linear features have a close relationship with the general morphology of the basin. Table V presents the main links between the terrain morphology characteristics and the linear feature trends.

The NE–SW and ENE–WSW trends are parallel to some major streams, slope orientations and topographic alignments. As an example, in the area to the north of Benamurel, the Rio Guardial is associated with a

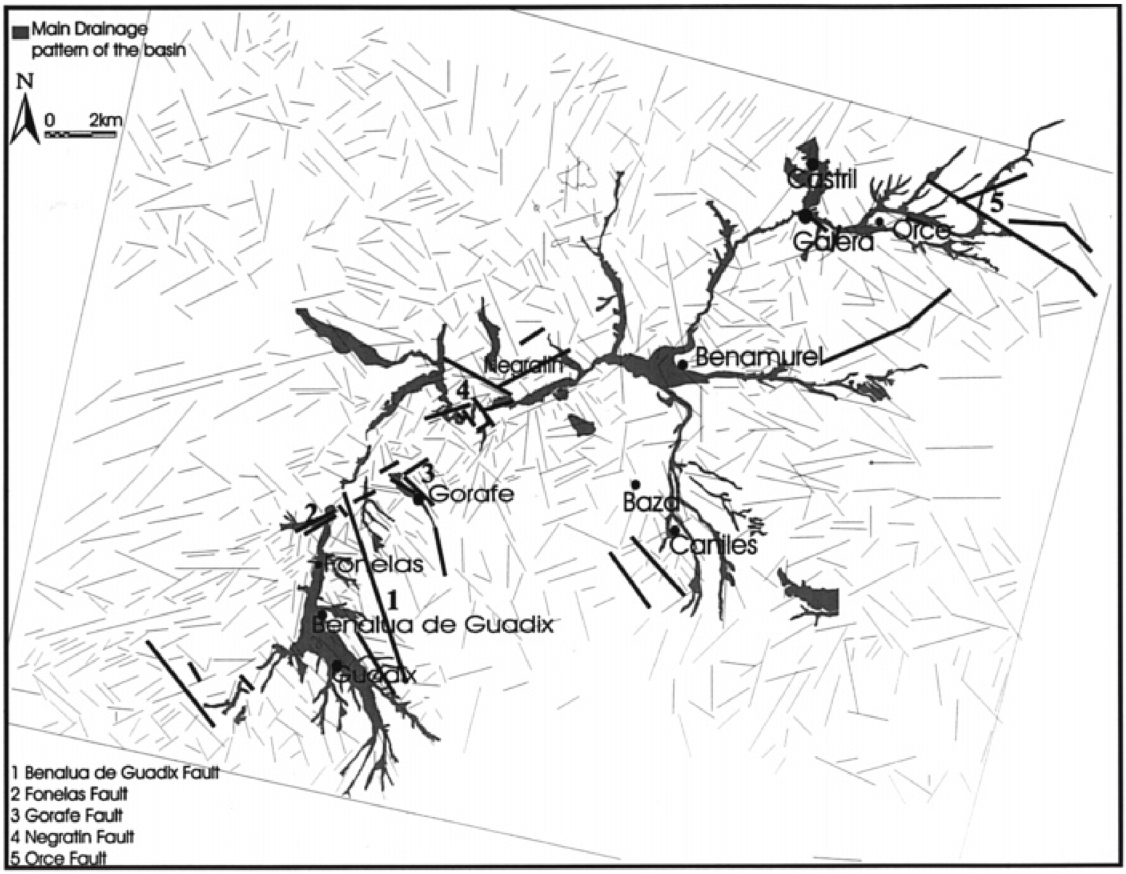

Figure 4. Lineament map overlying the main drainage features of the Guadix-Baza basin (the lineament map limits extend beyond the basin borders)

lineament which extends to the Castellijar village and parallel to it is an alignment of topography represented by the pediplane level. Another example is in the vicinity of Fonelas and Benalua de Guadix where two major lineaments are represented by topographic alignments. In the Guadix area the NW–SE linear features are associated with extensive faults, which may be part of a regional extension. This was the case of the Fonelas fault set where linear features coinciding with this set of faults are associated with fracturing. In the Baza and Huescar area they appear to be associated with the drainage orientation. This trend indicates a dextral strike-slip movement.

The NNE–SSW and WNW–ESE trends are represented by most of the valley-bottom alignments and scarp edges. From a geomorphological point of view these trends are the most important in the whole basin. Although they are not present in all parts of the basin, they are present in Quaternary materials, such as the pediplane level, and some of them are also present in recent deposits such as glacis and alluvium. These two trends together form a conjugate system, which may be related to the neotectonic stress field. The minor trends, although they are less numerous, define some of the most important faults of the basin. Some of the recent faults, observed in the Negratin area, take this trend as well. The NNE–SSW and the NNW–SSE trends seem to have a major control over the morphology of the badlands areas where the cuestas forming the bulk of the badlands generally take this orientation. However, these trends are not common in the as a whole basin and they occur only in the recent material of Pleistocene age. The E–W and N–S trends are present but not in all areas. These two trends are associated with the most recent faulting in the Negratin and Huescar area (Figure 4).

DISCUSSION

The tectonic processes that have affected the basin occurred during Plio-Pleistocene and Holocene times and are in large part responsible for the basin's present topographic form. The last major tectonic event was the uplift of the basin during the Quaternary leading to the formation of the present drainage pattern. The uplift coincided with the changes in direction of the principal stress during the Quaternary, when most of the identified faults within the basin were created. As a result of the Quaternary tectonic uplift, which occurred throughout the Betic Cordillera, the streams and rivers incised into the landsurface about 30 to 80 m below the Pliocene–Pleistocene pediplane level. The erosional pattern formed along lineaments, which appeared during Quaternary time. The faults formed during this period controlled the orientation of the drainage system. Because of the highly erodible nature of the sedimentary formations in the basin, evidence for offset or movements tends to be obscured by erosion of the weak sedimentary formations. Consequently, fractures and faults are difficult to detect by conventional field studies.

The fact that the lineament trends can be correlated to major tectonic features of the study area and also the whole Betic Cordillera is a strong indication that the majority of lineaments are fault-related. The trends appear to represent conjugate systems which are well expressed in several parts of the basin. In the Guadix area of the basin, two prominent sets of lineaments belonging to this conjugate system are named in this study as the Fonelas fault zone. The first one is the Benalua de Guadix lineament (Figure 5), located just east of the village of the same name, running roughly NW–SE. The second one is the Fonelas lineament (Figure 5), located north of the village of Fonelas, running SW–NE. The lineaments are considered to be related to buried or hidden faults. This pattern of a conjugate system of faults is common throughout the basin.

In the area of the Negratin fault zone, the Pliocene/Quaternary sequences are well cemented with the result that the faults are not obscured; several prominent lineaments have been checked in the field and have been recognized as faults. Also a number of recent faults affecting Holocene deposits were recognized in the vicinity of the Negratin dam. The area is affected by intense faulting and folding and some of the beds of the Guadix formations are almost vertical. The area itself belongs to a large anticline of Miocene age affected by salt intrusion (diapirism) all around the fault zone.

In the Gorafe area, which occupies the centre of the Guadix-Baza basin, there are further examples of the effect of the lineaments on the morphology. For example, in the vicinity of Gorafe, the Rio Gor is 60–70 m below the pediplane level where a massive landslide occurs on the western side of the valley; the landslide appears to be controlled by faulting. To the east of Gorafe towards the Negratin dam (Figure 5), the landsurface is considerably affected by lineaments giving a cuesta-shaped landscape. The poorly cemented fluvial and lagoonal materials eroded rapidly as a result of early to late Quaternary uplift and tectonic activity. These Negratin, Gorafe, Fonelas faults, appear to be members of one continuous fault zone which affects the whole basin roughly in SSW–ENE or SW–NW directions. The zone is considered to represent the limit between the Internal and External Zones.

Investigation of the area of the Guadix-Baza basin has shown that most of the lineaments detected on the satellite imagery are of tectonic origin (Tables V and VI). The landsurface is considerably eroded where the lineament density is high; this coincides usually with an underlying major basement fault, which probably represents the contact between the Internal and External Zones. The lineament density has played a major role in shaping the basin; along the entire centre of the basin where the lineaments are densest, the landscape is chaotic with lowland areas and cuesta-shaped relief. Where the lineaments are less abundant the landscape, apart from large and long scarps, is unaffected and the surface is almost horizontal along the edges of the basin. Lineament orientation follows the same trend as the fault system of the Betic Cordillera and, hence, appears to be tectonically related (Table VI).

CONCLUSION

Recent tectonic processes have had a major influence on the geomorphology of the study area. The lineaments created by recent and earlier tectonic processes have controlled, to a great extent, the alignment of the main valley systems and the pattern of the tributaries of the drainage system, and the general shape of the

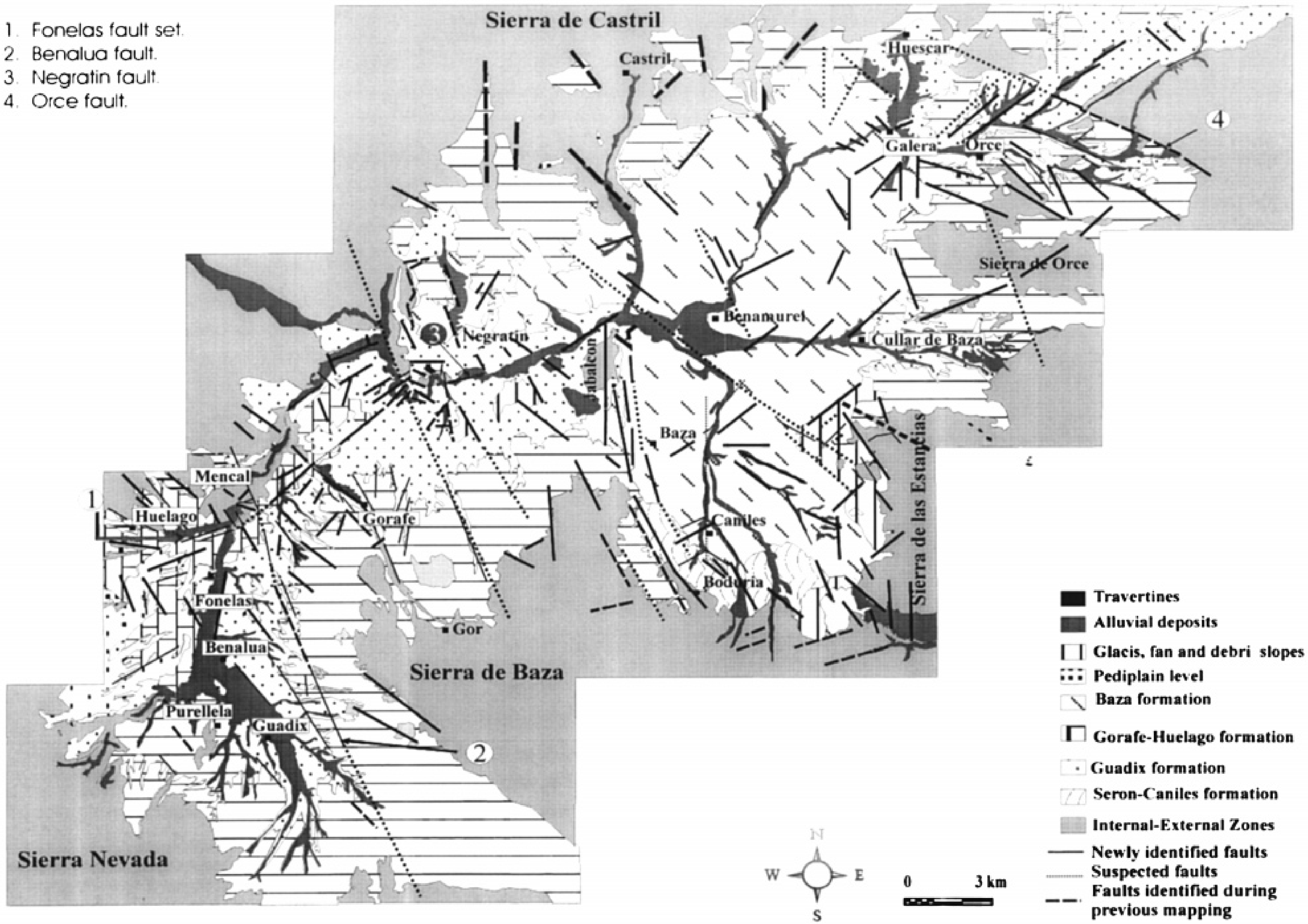

Figure 5. Geological map of the Guadix-Baza basin showing the newly identified faults

Table VI. Relationships between lineament orientation, tectonic geomorphology and Badlands areas (lineaments less than 500 m are not included)

Sets	Strike	Length (km)	Percentage	Tectonic association	Density	Geomorphic expression	Relation to Badlands
i	NE–SW	2 to +5	30 to 35	Parallel to regional faults Parallel to drainage orientation a and some basement faults	High	Follows major streams and valleys Extensive in dune-shaped ‘Badlands’	Predominant at Huelago, Gorafe and Negratin.
ii	NW–SE	1·5 to 2	20 to 25	Parallel to the Negratin fault Parallel to the Fonelas fault	High	Follows some major streams meanders Valleys and hill edges.	Predominant in nearly all Badlands areas.
iii	ENE–WSW	1·5 to 2·5	Average of 20	Parallel to some basements	Medium	Scarp edges Valley bottoms.	Low presence
iv	NNW–SSE	0·5 to 1·5	10 to 15	Parallel to some drainage orientation and some basement faults	Low	Stream meanders Scarp edges.	Occasional presence near Negratin dam, Beas de Guadix and Baza area
v	NNE–SSW	1 to 2	5 to 10	Parallel to drainage orientation	Low	Valley bottoms and scarp edges	Minor
vi	WNW–ESE	1 to 3	~5	Parallel to drainage lines and some Pleistocene faults	Low	Scarp edges and straight stream lines	High presence in the area of Gaudix
vii	E–W and N–S	1 to 3	~5	Parallel to drainage lines	Low	Valley bottoms and scarp edges	Fair presence

landsurface. The broad geomorphological pattern of the basin characterized by the presence of badlands or of cuesta topography is the result of tectonic activity within the area during Pliocene–Quaternary time. Erosional effects including mass movements in the Guadix-Baza basin occurred along lineaments, which appeared during Pliocene–Quaternary time. These lineaments facilitated the incision of streams and the creation of wide valleys.

Satellite imagery can be used effectively in delineating linear features, which provide an explanation for geomorphological features, break of slope, streams, landslides and landscape patterns. The technique developed here is useful, especially for more easily eroded rocks. This is because lineaments can be defined from a combination of pieces of evidence, which are not discernible in the field or are on adjacent areas of competent rock. Nevertheless, there is a need for further work to establish interpretative procedures for such rocks

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